

## **Alkali-activated concrete for the production of building blocks: research achievements and future challenges**

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### **ABSTRACT**

Several global challenges identified by the UN Sustainable Development Goals are either directly or indirectly linked to the construction sector. The need for decent and affordable houses is an urgent problem for many developing countries, whereas the concerns about the carbon emissions related to the manufacture of Portland cement are growing worldwide. A number of possible solutions are currently offered by the research, which has been investigating the recycling of waste/by-products into sustainable building materials during the last decades. This paper discusses the experience gathered in the manufacture of building blocks using alkali-activated concrete produced from waste streams such as fly ash, slag, or cement kiln dust. Laboratory investigations on binder development, concrete mix proportioning, and building block sample production, as well as full size factory trials with industrial equipment, were carried out for assessing the potential and the challenges of this technology. Obtained results demonstrated the technical feasibility of manufacturing building blocks with alkali-activated concrete, and highlighted the challenges for a viable and sustainable application of this technology.

### **1. INTRODUCTION**

According to the 2018 revision of the UN World Urbanisation Prospect, urban population is estimated to exceed 65% of the total world population by 2050. This growth is driven by two factors: world population increase and urbanisation rate. Global urban population is expected to increase by 2.5 billion by 2050, with Asia and Africa accounting for almost 90% of this growth [1]. This urban development comes at a social cost: more than 1.3 billion of people live in slums over the world, and the projected figure is over 2 billion people by 2050. These social phenomena are therefore closely connected to the need for decent and affordable housing, and thus to the construction sector and the choice/availability of building materials. The use of Portland cement (PC) based materials in building has two main drawbacks: (a) its availability and cost in developing, land-locked countries with poor infrastructures that are fully dependent on import, (b) the environmental impact of the production of PC. Due to the de-carbonation of limestone and the burning of fuel for the heating of kiln (around 1450 °C), about 1 tonne of CO<sub>2</sub> is emitted for each tonne of PC produced and this results in 8-10% of the total CO<sub>2</sub> emissions [2]. Use of local building materials in developing countries has been investigated and discussed in the literature [3, 4]. Despite several advantages, some issues were highlighted for the use of alternative building materials, i.e. their relatively low mechanical properties, the durability, the non-homogeneity of natural materials, and the lack of industrial quality control.

Concrete is still the preferred option for construction, being one of the most versatile, strong and durable material currently available at reasonable cost. Despite the high carbon emissions associated

for the production of clinker, concrete has a lower embodied energy than other building materials such as steel, bricks or glass [5]. Avoiding the clinker, and thus substituting Portland cement with other binders, can solve the environmental issues of concrete without losing the advantages from its use.

In the last decades, a class of novel materials called alkali-activated binders (also known as ‘geopolymers’) have received growing interest from researchers and industry. The main concept is to exploit the reaction happening between aluminosilicate materials (called precursors) and alkali chemicals (called activators) to produce a solid, dense binding matrix whose properties can exceed the ones of PC [6]. Precursors can be sourced from waste streams or by-product that are readily available from existing industries. These include fly ash (FA) and ground granulated blast furnace slag (GGBS). Waste-stream pozzolans such as FA are not fully recycled into value added products yet, and excesses are stockpiled or landfilled [7]. Alkali-activated binders can provide a desirable alternative to PC binders, not only for the environmental benefits arising from the avoidance of CO<sub>2</sub> emissions associated with PC production, but also in terms of their performance and durability, where such properties are often better than those of PC [8].

Cement kiln dust (CKD) is another pozzolanic waste stream that received attention for its recycling potential. Its chemical composition is not dissimilar to that of Portland cement [9]. When only traditional fossil fuels were used in the kiln, a high fraction of produced CKD was recycled back in the PC production. However, the use of alternative fuels in modern plants resulted in excess alkali, chlorides and sulfates that do not allow full recycling directly in the process. Due to the very high volume produced worldwide, CKD landfilling has become an environmental issue, and several reuse/recycle strategies have been proposed in the past 35 years, from agricultural applications and soil stabilisation to concrete production. This latter has been investigated worldwide in recent years [10], as a supplementary cementitious material with PC [11], in blended binder formulations with slag [12] or with other industrial wastes. The use of CKD as component for alkali-activated binders was also studied for assessing the activation potential with slag [13], fly ash [14] or fly ash-slag blends [15].

When investigating potential waste/by-products recycling options, issues such as logistics, production protocols and market opportunities need to be taken into account. Need for careful control of mix proportions, handling of alkali chemicals, narrow workability time windows, or need for temperature curing, are all factors suggesting that the best environment for alkali-activated concrete production is the precast industry rather than the ready-mix (on-site pouring). Waste rarely has a consistent and controlled composition, therefore the inherent variability of its quality calls for a safe margin when mechanical properties of the output products are determined. Furthermore, the largest market share of the precast concrete industry is commonly taken up by masonry/concrete blocks. For these reasons, the most promising application for a fast-track market uptake of waste-derived concrete is the production of alkali-activated building blocks, although the narrow profit margin on this product might be an issue. Economic aspects will be discussed in later sections.

This paper describes the experiences gathered in the production of alkali-activated concrete building blocks in recent research projects carried out at Queen’s University Belfast. The first case study was developed in the framework of the research activities of the EC FP7 funded SUS-CON project (2012-2015) and involves the use of FA/GGBS activated with commercially available chemicals. Further experience was gathered in the InnovateUK/EPSRC funded RESCIND project (2015-2017), that focussed on assessing the recycling potential of CKD in alkali-activated concrete applications.

## **2. MATERIALS AND METHODS**

### **2.1. Materials**

#### *2.1.1. Fly ash and GGBS*

Fly ash (FA) is a by-product generated by the combustion of pulverised fuel (typically coal) in power plants. Its chemical composition varies according to the nature of the fuel and its grade. Main

components in terms of oxides are silicates, alumina and calcium oxide, resulting from coal-bearing rock strata. Fly ash was supplied by Power Minerals Ltd. – former Hargreaves Company, Drax Power Station, North Yorkshire, UK.

GGBS is obtained by quenching molten iron slag (a by-product of iron and steel-making) from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder. The chemical composition of a slag varies considerably depending on the composition of the raw materials in the iron production process. GGBS was supplied by Civil and Marine Ltd – Hanson Company and member of the HeidelbergCement Group, West Thurrock, Essex, UK.

Chemical analysis via X-Ray Fluorescence method (XRF) identified the oxides composition of the raw materials, see Table 1.

### 2.1.2. Cement Kiln Dust

CKD, also known as cement flue dust, or by-pass dust, is a secondary material generated during the production of Portland cement. It is collected in the air control devices downstream the kiln. The appearance is a grey-tan micron-sized powder with very high specific surface. CKD was supplied by Lagan Cement at the factory in Kinnegad (Republic of Ireland). Its oxide composition, obtained with XRF analysis, is shown in Table 1.

**Table 1.** Major oxides composition (in percentage) as per XRF analysis on the investigated materials

Material	CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	MgO	TiO <sub>2</sub>	MnO	Cl	Others
FA	2.24	46.78	22.52	9.15	0.89	4.09	0.9	1.33	1.05	0.05	-	11.00
GGBS	43.72	29.38	11.23	0.36	1.05	0.93	1.76	6.94	0.67	0.51	-	3.45
CKD	57.26	18.24	4.32	2.59	0.88	6.26	3.49	0.78	0.33	0.08	5.55	0.22

### 2.1.3. Alkali chemicals used for activation

Commercial products were used as activators, namely solid NaOH at commercial grade (99% purity) and Sodium Silicate solution with SiO<sub>2</sub> : Na<sub>2</sub>O ratio = 2:1 (Na<sub>2</sub>O 12.8%, SiO<sub>2</sub> 25.5%, water 61.7%), provided by Fisher Scientific. NaOH solution was prepared at 30% w/w.

The parameters adopted for determining the activator dosage were the alkali dosage and the alkali modulus. Alkali dosage (M<sup>+</sup>) was defined as the mass ratio of total sodium oxide (Na<sub>2</sub>O) in the activating solution to the binder. Alkali modulus (AM) is the mass ratio of sodium oxide to silica in the activating solution.

### 2.1.4. Aggregate

Aggregate was supplied by CES Quarry Products Ltd (Northern Ireland). It was a mix of quarry dust, 6 mm and 10 mm basalt crushed rock. The aggregate used for the factory trials at Lagan premises was supplied by Lagan (currently Breedon Group) at the building block factory site, as a mix of sand and crushed basalt.

## 2.2. Methods

### 2.2.1. Laboratory production of building blocks

A rig for the vibro-compaction of building blocks was developed in the laboratory for manufacturing samples mimicking the industrial process for building block production, see Figure 1. Dead load for compacting purposes was about 1 kN (about 100 kg mass), acting on a electric hammer with output power 800 W and rate of percussion 975-1950 min<sup>-1</sup>. The concrete mix was cast in stainless steel moulds with a section area of 225 x 100 mm, allowing to compact blocks with a height of about 220 mm (i.e. half height of commercial blocks, whose dimensions are approx. 440 x 215 x 100 mm).

The procedure for the block production was as follows:

1. Aggregate was mixed in a planetary pan mixer, pre-wetted at 1% w/w with water.
2. Binder powders were added and mixed for additional 3 minutes.
3. Alkali activator solution and required water were added, mixing for further 5 minutes.
4. After a qualitative consistency test, moulds were filled up to a pre-determined weight of 10 kg (fig 2.a).
5. The mould was placed under the vibro-compaction hammer (fig 2.b) and compaction at 1560 strokes per minute was applied for 30 s (fig 2.c).
6. The block was then demoulded (fig. 2.d). Curing regimes varied.



**Figure 1.** Vibro-compaction rig for the building block production



**Figure 2.** (a) Mould filling; (b) mould positioning; (c) vibro-compaction; (d) demoulding.

#### *2.2.2. Mix proportions for FA/GGBS concrete blocks*

Several mix parameters were tested for delivering suitable mix proportions for alkali-activated building blocks. An extensive research aimed at understanding the behaviour of FA-GGBS blends [16] informed on suitable pre-selection of blends with GGBS proportions varying from 20% to 70%. Activator dosages were fixed at  $M+ = 7.5\%$  and  $AM = 1.25$ . Curing conditions and binder content (per  $m^3$  of concrete mix) were also investigated for ensuring the suitability of the proposed formulation in achieving technical requirements comparable to those of commercial building blocks.

Two mixes were further investigated: a 190 kg/m<sup>3</sup> blend of FA/GGBS 60%/40% and a 160 kg/m<sup>3</sup> blend of FA/GGBS 30%/70%. Five curing conditions were investigated: (a) 1 day in oven, remaining days at room conditions; (b) 3 days in oven, remaining days at room conditions; (c) 3 days in sealed bag, remaining days at room conditions; (d) 7 days in sealed bag, remaining days at room conditions; and (e) full time room conditions. Obtained compressive strengths and block densities are shown in Table 2.

**Table 2.** Compressive strength and density of investigated mixes vs curing conditions. UCS = uniaxial compressive strength.

Curing type	Binder content (kg/m <sup>3</sup> )	Binder composition	UCS 7 days (MPa)	UCS 28 days (MPa)	Density 7 days (kg/m <sup>3</sup> )	Density 28 days (kg/m <sup>3</sup> )
a	190	60/40 FA/GGBS	8.3	8.3	1990	2010
b			7.9	6.1	1935	1945
c			7.7	9.4	2075	2055
d			5.7	8.2	1990	1990
e			6.7	8.6	2000	2000
a	160	30/70 FA/GGBS	8.1	7.9	1935	1970
b			6.2	7.5	1930	1910
c			6.8	9.8	1950	2000
d			10.6	13.2	2015	2005
e			6.2	7.0	1935	1935

Considering the need for matching both the compressive strength (target 7 MPa at 28 days) and the density (target 1950 kg/m<sup>3</sup> at 28 days), as well as the cost of the binder and the curing conditions on site, the mix with 160 kg/m<sup>3</sup> of 30/70 blend was selected for the factory trials.

### 2.2.3. Mix proportion for FA/GGBS/CKD concrete blocks

Several parameters were investigated for optimising the mix proportions for factory trials, namely the blend composition (CKD, FA and GGBS relative proportions), water content, inclusion of chemicals for enhancing the activation, and curing regimes. Preliminary experiments suggested that neat CKD was not able to provide sufficient activation to FA or FA/GGBS blends for ensuring satisfactory early age strength at room temperature. In order to reduce the cost of activators and to improve the environmental benefit of the waste recycling into concrete blocks, a novel powder was developed through a thermochemical process able to transform waste glass and sodium hydroxide in highly reactive solid sodium silicate [17]. Four binder contents (100, 150, 175, and 200 kg/m<sup>3</sup>) were tested with the following binder composition: CKD 50%, GGBS 35%, FA 15%, activator dosages M+ = 4% and AM = 1. Obtained compressive strengths and block densities are shown in Table 3.

The density of blocks produced in the laboratory was higher than the target density in order to obtain the required strength. The mix selected for the factory trials had 175 kg/m<sup>3</sup> of binder composed by CKD 50%, GGBS 35%, FA 15%.

**Table 3.** Compressive strength and density of investigated mixes vs curing conditions. UCS = uniaxial compressive strength.

Binder Content kg/m <sup>3</sup>	UCS 1 day (MPa)	UCS 7 days (MPa)	UCS 28 days (MPa)	Density 1 day (kg/m <sup>3</sup> )	Density 7 days (kg/m <sup>3</sup> )	Density 28 days (kg/m <sup>3</sup> )
100	1.7	3.3	n.t.	2045	2015	n.t.
150	6.1	7.1	11.0	2165	2060	2155
175	5.4	9.0	n.t.	2110	2150	n.t.
200	7.0	10.2	14.6	2150	2180	2225

#### 2.2.4. Factory trial for FA/GGBS concrete blocks

The up-scale production of alkali-activated building blocks was carried out at CES Quarry Products Ltd (Northern Ireland) premises. The main factory facilities utilised for the trials were the mixing station, the block machine and the block machine loader (see figure 3). In order to reduce the volume of chemicals and binders to be used for the test, brick-sized blocks having dimensions 95 x 210 x 65 mm were cast instead of building blocks of dimensions 440 x 215 x 100 mm (standard blocks), thus the required quantity of mix was 180 litres per batch. More than 500 brick-sized blocks were manufactured during the trial.



**Figure 3.** Mixing station, the block machine and the block machine loader.

Two mixes were investigated with water-to-solid ratios of 0.38 and 0.34. Binders and chemicals were poured manually in the mixer, whilst aggregate and water were added by the automatic dosage system. Two batches of bricks were manufactured with each mix, in order to compare two different curing regimes, i.e. sealed and open air respectively. Ordinary Portland cement (OPC) bricks were cast as a reference product for comparing the mechanical and physical properties of alkali-activated concrete bricks.

#### 2.2.5. Factory trial for FA/GGBS/CKD concrete blocks

Factory trials for the FA/GGBS/CKD concrete blocks were carried out at the Lagan (currently Breedon Group) concrete block production unit in Whitemountain (Temple quarry), Lisburn (Northern Ireland). Binders were prepared in 1-tonne bags, and the activator was added just before the mixing step. Three batches of about 1.4 m<sup>3</sup> each produced nearly 400 blocks 440 x 215 x 100 mm. A crane lifted the bags above the mixer where aggregate and water were added by the automatic system, then



the powder was poured in from the top of the mixer. The mix was then transferred to the loading car through the hopper, and the block machine was fed on the yard. Three bales were produced for each mix, see Figure 4.



**Figure 4.** Factory trials for the production of FA/GGBS/CKD building blocks.

### 3. RESULTS AND DISCUSSION

#### 3.1. Factory trial with FA/GGBS concrete blocks

Brick-sized blocks from the four production batches (batch 1: sealed ‘wet’ mix; batch 2: air cured ‘wet’ mix; batch 3: sealed ‘dry’ mix; batch 4: air cured ‘dry’ mix), along with OPC brick-sized blocks, were sampled and tested for compressive strength at 4, 7, and 28 days, see Table 4. Figure 5 shows produced blocks in the factory yard.

Samples from batch 1 showed very high strength (17 MPa and 19.5 MPa after 7 and 28 days respectively) compared to samples from other batches and OPC, presumably due to the higher density obtained during prolonged compacting operations. The different consistency of the mix misled the operator to increase the compaction time. Curing in sealed conditions has a beneficial effect on the strength development, as batches 1 and 3 (cured in boxes) gave higher strength results than batches 2 and 4 (cured in air). Comparing the results from ‘wet’ and ‘dry’ mixes, it was observed that this latter gave lower strength both in sealed (batch 1 vs. batch 3) and air cured (batch 2 vs. batch 4) conditions. This might be due to a longer time spent in the mixer for the ‘dry’ mix, during which reactions started and thus the blocks were not properly compacted.

Alkali-activated blocks show higher or at least equal strength in respect with OPC blocks in all cases but for batch 4. This could be due to the combined effect of a poor mixing step (chemicals and binder stayed in the mixer for long time without water addition, and this can have triggered the reaction) and curing conditions (air curing).

**Table 4.** Compressive strength and density of brick-sized blocks from factory trials. UCS = uniaxial compressive strength.

Batch	UCS 4 day (MPa)	UCS 7 days (MPa)	UCS 28 days (MPa)	Density 4 days (kg/m <sup>3</sup> )	Density 7 days (kg/m <sup>3</sup> )	Density 28 days (kg/m <sup>3</sup> )
OPC	7.0	6.1	7.9	1865	1880	1890
Batch 1	15.4	17.0	19.5	2130	2120	2100
Batch 2	9.0	8.5	8.5	1925	1945	1860
Batch 3	8.5	8.2	11.4	1935	1930	1905
Batch 4	5.6	6.5	7.6	1815	1825	1840



**Figure 5.** Block produced during factory trials. The wooden boxes were used for investigating sealed curing conditions.

### 3.2. Factory trial with FA/GGBS/CKD concrete blocks

Factory trials took place at the beginning of November 2017. Three mixes were carried out with varying water contents in the mixer according to the experience of the operator. Mix 1 was considered too wet, but mixes 2 and 3 were deemed to behave satisfactorily by the plant operator and project staff, see Figure 6. The weather conditions during the factory trial and in the week immediately after that were bad, with average temperature of 8°C, being as low as 1°C at night.





**Figure 6.** FA/GGBS/CKD blocks produced during factory trials.

Compression tests on produced blocks were carried out at day 4 and day 7 both at industrial premises and at university laboratory. Since mix 1 was assumed to be too wet and therefore below the expectations, only blocks from mix 2 and 3 were tested. The obtained compressive strengths were disappointingly low. Strengths at 4 days were in the range 1 – 1.5 MPa, whilst strengths at 7 days were in the range 2 – 2.5 MPa. Furthermore, it was observed that the core of blocks was significantly moist even after 7 days of curing. Two explanations for the obtained results were: (1) the weather conditions might have hindered the development of the reaction; and (2) the extra water from the aggregate and the environmental moisture might have negatively affected the reaction.

Results obtained from the factory trials allowed to revise the formulation at laboratory level, including the check of sub-optimal curing conditions.

#### **4. CHALLENGES FOR THE INDUSTRIAL UPTAKE OF THE TECHNOLOGY**

As discussed in section 1, in order to ensure the success of recycling technologies, several economic and management factors need to be taken into account along with the technical feasibility. Considering the current limitations on the control of the fresh properties, of the curing and on the need for very careful mix proportioning, the preferred development for alkali-activated concrete is for precast production. An initial target application for alkali-activated concrete is therefore envisaged to be dense aggregate concrete blocks. The choice of a low cost commodity product can mitigate commercial risk, whereas the use of waste-derived, alkali-activated concrete in demanding structural, reinforced, precast or site cast applications would introduce additional technical risk. Building blocks represent by far the most produced precast concrete product their production is relatively simple and the technology is already available worldwide.

On the other hand, building blocks are very cheap building elements, and the profit margin is typically very narrow. Any extra cost due to a change in the mix proportioning can impact on the unit cost and thus push the product out of the market. The first and foremost challenge is therefore to produce

alkali-activated building blocks keeping their final cost in line with market competitors. Some considerations are:

1. There are fundamental geographic limitations to the exploitable market from any concrete product production facility. Low margins and transportation costs tend to “pin” suppliers to a local area. The UK’s Concrete Block Association suggest that there are 100 producers in the UK who serve an average radius of only 30 miles. Consequently, the manufacture facilities need to be very close to where raw materials (FA, GGB, CKD, other waste/by-products) are produced as well as to the designated market.
2. Avoiding the landfill of waste/by-products and therefore fostering the development of a local industrial symbiosis has an economic value that needs to be factored in. Savings from landfill costs or from environmental taxes, and benefits from reducing the consumption of virgin materials can offset the production costs and thus make the production viable.
3. The main cost for alkali-activated concrete production is typically represented by the use of chemicals for the activation. The development of suitable, low-cost and low-carbon activators is therefore crucial for ensuring the industrial uptake of alkali-activated concretes. A number of researches successfully delivered alternative activators where silicates have been sourced from waste streams [17-21]. It is important to observe that sourcing activators from waste stream not only can contribute to keeping the cost of concrete low, but also can reduce the CO<sub>2</sub> emissions of alkali-activated concrete, which is an essential condition for effectively reducing the carbon emission of the construction sector [22].

## 5. CONCLUSIONS

This paper described and discussed the experience gathered in research projects aiming at the development of alkali-activated concrete blocks and at their demonstration in industrial environment. Large factory trials (with the production of a significant number of blocks) allowed to confirm the technical feasibility of alkali-activated concrete use in the manufacture of building blocks. The smooth execution of the site production tests confirmed that the technology is easily transferrable from laboratory to factory, without requiring significant modifications to the existent industrial equipment and facilities. Very few examples of real size full scale production tests are available in the technical literature, and the information that can be obtained from such exercises is precious.

FA/GGBS mixes activated with commercially available chemicals exceeded the expectations in terms of mechanical strength of blocks, confirming that alkali activation is a mature technology with high potential. The use of CKD proved to be more challenging, and factory trial sub-optimal results underlined the importance of controlling each step of the production, from the mixing to the curing, as adverse weather conditions and uncertainties of the moisture content of the aggregate negatively affected the performance of building blocks.

If the technical feasibility of manufacturing building blocks with alkali-activated concrete has been proved, the main challenge to the industrial uptake of this technology relates to the control of production costs for entering a very competitive and low-profit market. The assessment of local conditions (in terms of availability of raw materials and proximity to the market) and the opportunities from avoiding landfill taxes or other incentives to recycling are fundamental in a market where every penny can make the difference. The most promising development in the sector is undoubtedly represented by the possibility of sourcing activators from waste stream, thus reducing their cost, curbing the CO<sub>2</sub> emissions of concrete and fostering virtuous circular economy loops.

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